Vibration analysis of a small diesel engine using diesel-biodiesel fuel blends

B. Heidary[1*], S. R. Hassan-beygi[1], B. Ghobadian[2], A. Taghizadeh[3]

(1. *Department of Agriculture Technical Engineering, College of Abureihan, University of Tehran, Tehran, Iran;*
2. *Department of Mechanics of Agricultural machinery Engineering, College of agriculture, University of Tarbiat Modarres, Tehran, Iran;*
3. *Department of Agricultural Machinery Engineering, Gorgan University of Agricultural Science and Natural Resources , Gorgan, Iran*)

Abstract: Biodiesel as an environmentally friendly fuel has the potential to provide comparable engine performance results. Biodiesel is a renewable fuel produced from vegetable and seed oils, animal fats or waste edible oils. Sound and vibration caused by the combustion process in the engine might have direct effects on users. One of the important characteristics of diesel fuels is high noise and vibration. The present study was carried out to examine the vibration of different diesel-biodiesel fuel blends in power tiller engine. The main goal was to present fuels with the minimum vibration. So, the time domain signals were analyzed in five levels of engine speed, three axes and six fuel blends on the engine. The signal processing and statistical approach were applied for data analysis. The results showed that in all engine speeds, the dominant frequency is matched to the piston stroke frequency of the engine, as well as the frequency of vibration with the increase of engine speed. The experiments indicated that the magnitude of vibration in the power tiller engine depends on the axis of measurement, engine speed and the fuel blends. Vibration acceleration is significantly affected by engine speed and the increase in forward speed due to the increase in vibration acceleration rms. The results of the experiments revealed that vibration acceleration is significantly affected by the axis of measurement. The magnitude of vibration acceleration in vertical axis was more than that in the other two axes and magnitude of vibration acceleration in the longitudinal axis was more than that in the lateral axis. Fuel blends had significant effect on the vibration. It demonstrated that B100, B5 and B20 have the lowest vibration. On the contrary, B15 and B10 have the highest vibration.

Keywords: vibration analysis, power tiller, time domain, frequency domain, diesel-biodiesel fuel blends

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1 Introduction

Research on renewable fuel “Biodiesel” is deemed to be essential in the present world. The term “biodiesel” commonly refers to fatty acid methyl or ethyl esters made from vegetable oils or animal fats, whose properties are good enough to be used in diesel engines (Lapuerta et al., 2008). Biodiesel has been considered as an ideal alternative fuel for diesel fuel in Iran. Biodiesel is an environmentally friendly fuel and has the potential to provide comparable engine performance results (Safiedinet al., 2011). Biodiesel has much less air pollution due to its higher oxygen content and less aromatic compounds and sulfur. One exception to this is nitrogen oxide (NOx) emissions, which is slightly higher during the biodiesel usage. Proper tuning of the engine can minimize this problem (Xue et al., 2011; Dwivedi et al., 2011; Pehan et al., 2009; Lapuerta et al., 2008). However, the other three kinds of regular exhaust emissions, particulate matter (PM), hydrocarbons (HC) and carbon monoxide (CM) are significantly reduced by biodiesel (Knothe, 2010). The decrease of fossil fuels could considerably reduce pollutants; this can be realized by replacing fossil fuel with renewable fuels. Sustainable renewable energy sources will play a key role

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*** Corresponding author: B. Heidary,** Email: bahareh_celestial@yahoo.com.

in the world's future energy supply (Najafi et al., 2011).

On one hand, the problem of air pollution exists in big cities of Iran (Tehran, in particular, always face severe air pollution in winter). On the other hand, the growth of Iran's economy has been the cause of the increase in energy consumption and Iran is facing danger of the decline of the fossil fuel resources and the increase of air pollution in big cities of Iran. Hence, Iranian universities and Research centers have been working on projects, so as to get new energy resources from biofuels. Biofuel project is being carried out by researchers at Tarbiat Modares university, Tehran university and Shiraz university. In Iran, biofuel has great potential to improve energy resources based on agricultural materials (oil seeds) and algae.

Oil seeds are harvested manually in Iran every year. Around 1 million ha of land from 20 states are estimated to be potential land for growing oil seeds. These states can produce 3.67 million t (million ton) of oil seeds crops. This amount of oil seeds can potentially produce 721 million L (million liter) of biodiesel every year. Canola, cotton and soybean are the most favorable biodiesel production sources. Other potential oilseeds for biodiesel production in Iran are sesame, olive, sunflower, safflower, almond, corn, coconut. Fars, Khuzestan and Khorasan are the major identified oilseeds products provinces for raising oilseeds in Iran (Safiedin et al., 2011).

The most important part of a machine is its engine, and fuel affecting combustion is considered as the main factor. Using biodiesel as fuel in the engine can affect some engine's performance like vibration. Sound and vibration caused by the combustion process in the engine will have direct effect on users. Diesel engine noise and vibration can create harmful effects on hearing and user's body. This is specially observed in the engines with high compression ratios and fast rising combustion pressures (Taghizadeh et al., 2012). The most well-known clinical disorder caused by vibration exposure is vibration-induced white finger (VWF). Sometimes, this is known as "dead man's hand" or Raynaud's disease of occupational origin (Mansfield, 2005). Small diesel engines are widely used in power tillers. Power tiller is one of the most useful agricultural machinery. These kinds of tractors are suitable for small fields. Economic advantages and control abilities of power tillers in different conditions and roads lead to an increase in using these tractors for the transport of agricultural products and human beings in fields and rural roads (Dewangan and Tewari, 2009; Sam and Kethrivel, 2006). There are more than 120,000 power tillers in Iran (Hassan Beigi and Ghobadian, 2005; Hassan Beigi et al., 2009). The operators of power tillers are exposed to high levels of hand transmitted vibration. Working with this machinery for a long time causes many disorders, hurt different parts of the body such as: ear, spine and digestion disorders, and vascular disease (Sam and Kethrivel, 2006; Salokheh et al., 1995; Tiwari and Gite, 2002). Likewise, it decreases efficiency and work quality (Tewari et al., 2004).

Many experiments are performed, so as to show the effect of biodiesel on diesel engines. The impact of biodiesel usage can be shown on injection pressure and injection timing, power, fuel consumption and thermal efficiency, emissions, engine performances and vibration. The impact of biodiesel bulk modulus on injection pressure and injection timing was conducted in a research. The major findings of this study are aimed at utilizing biodiesel in mechanically controlled injection systems instead of blending with conventional diesel fuel involvements. In this research it was shown that the advances in the start of injection timing, using biodiesel rather than mineral diesel, are smaller than those calculated with standard methods and may not even occur at all. There is no doubt it depends on injection system design. In addition, they demonstrate that, contrary to common belief, injection pressure does not always increase when using biodiesel (Carsana, 2011). The effect of biodiesel fuels in diesel engine power, fuel consumption and thermal efficiency, emissions were investigated by so many researchers. They showed that engine power and torque tend to be 3%–5% lower when using biodiesel. Fuel efficiency tends to be slightly lower when using biodiesel due to the lower energy content of the fuel. Taghizadeh et al. (2012) evaluated the vibration of a tractor diesel engine using biodiesel and petrodiesel fuel blends. In this study, the maximum vibration accelerations were between 1,800 and 2,000 r min^{-1}. The results showed the total vibration values are reduced significantly after servicing the engine by 12%. Furthermore, the vibration levels are significantly varied with the fuel blends. Statistical analysis of data showed that the vibration was the lowest for B40 and B20. Similarly, B15, B30 and B50 had the highest vibration (Taghizadeh et al., 2012). Some other similar studies about power tillers have been carried out by other researchers as well (Dewangan and Tewari, 2009; Salokheh et al., 1995; Tiwari and Gite, 2002; Tewari et al., 2004).

The literature review indicated that the research related to the power tiller diesel engine vibration using biodiesel or the blends of diesel-biodiesel fuels has not been reported so far. Therefore, this study was conducted to measure the engine vibration acceleration performance of a power tiller and explore the different diesel-biodiesel fuel blends in stationary mode.

2 Formulation

The basis of machine vibration is the use of root mean square (rms), that can be represented as Equation (1):

$$a_{RMS} = \left[\frac{1}{T} \int_0^T a(t)^2 \, dt \right]^{1/2} \tag{1}$$

where, a_{rms} is the acceleration root mean square (rms) (m s^{-2}); $a(t)$ is measured acceleration domain (m s^{-2}) and T is measured acceleration period (s) (Mansfield, 2005).

For vibration assessments, individual measurements made in orthogonal axes should be combined (Mansfield, 2005). Vibration occurs in three translational axes and therefore the measurement should be performed in three axes, Lateral, Longitudinal and Vertical. The vibration total value (a_{total}) was described as total rms of three component's value and shows the total vibration acceleration of three axes. A_{total}, was determined in Equation 2 as below: [Dewangan and Tewari, 2009; Griffin, 1996; Goglia et al., 2006; ISO 5349, 2001].

$$a_{total} = [a_x + a_y + a_z]^{1/2} \tag{2}$$

where, a_x is total vibration acceleration in x axis in (m s^{-2}); a_y is total vibration acceleration in y axis in (m s^{-2}) and a_z is total weighted vibration acceleration in z axis in (m s^{-2}) (Mansfield, 2005).

3 Methods and materials

3.1 Power tiller engine

In this study, a single cylinder 13 hp power tiller, engine manufactured by Kubota Co. Japan, was used. Table 1 shows the technical specifications of the engine and power tiller during the experiments. The main moving components of the engine are pistons, connecting rods and crankshafts. Vibration in reciprocating engines caused by the changes in gas pressure inside the cylinder and alternating inertia forces concentration on different engine parts.

Table 1 Specifications of the power tiller under test

Engine manufacture	Dae Dong Industrial Co, Korea
Engine model	ND130
Engine Specifications:	Horizontal, water-cooled 4-cycle single cylinder diesel engine
Power at 2200 r min^{-1}:	13 hp
Number of cylinders:	Single
Stroke cycle:	4-Stroke
Air intake system:	Naturally aspirated
Displacement /cc:	673
Combustion chamber:	Direct injection
Cooling system:	Water cooled
Other Specifications:	Type of clutch: Dry, multi-plates

3.2 Biodiesel fuel

In this study, six fuel blends were prepared and used. These blends were, B5, B10, B15, B20, pure biodiesel (B100), and pure diesel. Diesel "D2" used in this research was refined and produced in Iran according to ASTM D975. Biodiesel used in this research was produced in the biodiesel laboratory of Bioenergy Research center, Tarbiat Modarres University (TMU), Tehran, Iran. In this center, biodiesel is produced from vegetable oils, animal fats, and also wastes oil based on ASTMD 6751-09 standard instruction and procedures. The specification of used diesel and biodiesel is shown in Table 2.

3.3 Equipments and procedure

The power tiller engine vibration was measured using three piezoelectric accelerometers with the specifications of CTC-AC102-1A (sensitivity, 100 mV g^{-1} – dynamic range, 50 g – source voltage, 18–24 V, range 0.5 to

Table 2 Specifications of the diesel and biodiesel used in tests

Properties	Diesel	Biodiesel
Density/g cm^{-3}	0.86	0.88
Viscosity/ $mm^2\ s^{-1}$:	3.3	4.73
Flash point/ ºC:	62	176
Cloud point/ ºC:	-5	-1
Pour point/ ºC:	-10	-4
High heating value/Btu gal^{-1}:	137	127

150,000 Hz, accuracy 0.1 m s^{-2}). Other facilities used for the experiments were a switch box, including three interface circuits for each accelerometer, supplied voltage for Accelerometer inputs and outputs, connectors for the PC, analog to digital converter A/D (Advantech, USB-4711A), optical-contact tachometer (Lutron DT-2268). Equipment used for the vibration measurement in tests is shown in Figure 1.

Figure 1 Vibration measurement and data acquisition set up

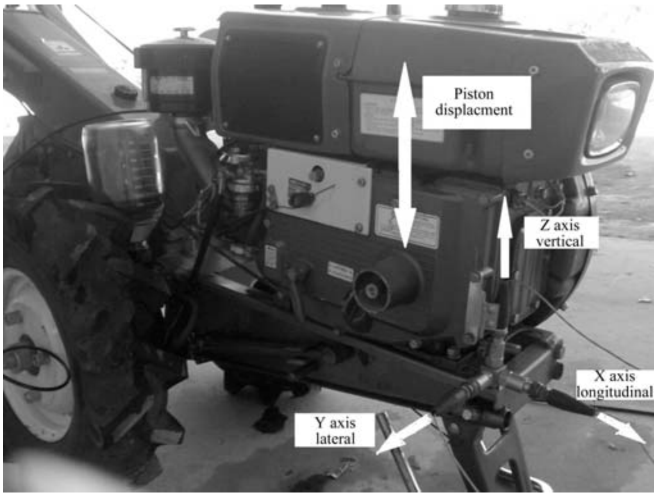

Figure 2 Monitoring of accelerometers and Orientation of measurement axes

Experiments were conducted at five levels of engine speeds (1,400, 1,600, 1,800, 2,000 and 2,200 r min^{-1}), six levels of consuming fuel blends (pure diesel, D, 5% biodiesel, B5, 10% biodiesel, B10, 15% biodiesel, B15, 20% biodiesel, B20, and pure biodiesel, B100). The vibration of a power tiller engine was measured in stationary mode on the asphalt surface in an open area. The recommendation of ISO 5349-2 (2001) was followed for orientation of the measurement axes (Figure 2). Z-axis was directed along the piston movement; Y-axis was parallelled to the longitudinal axis of the chassis and X-axis was perpendicular to the Z-axis and Y-axis.

3.2 Data collection and analysis

LABVIEW software program was used to control the A/D convertor and also showed and saved the data in laptop (sampling rate of 80,000, recording time of 2 s). The recorded digital time domain signals were further processed to calculate root mean square (rms) values of vibration acceleration. Then, the rms values of vibration acceleration were statistically analyzed using the three factors completely randomized design in SAS software, to study the effects of the engine speed, fuel type and measurement direction on the rms values of vibration acceleration. Further, the Duncan’s multiple range test was used to compare the means. The software that's used for converting the time domain signals to frequency domain signals was Matlab and data conversion was carried out by fast Fourier transform (FFT). Comparing the dependent parameters was so complicated that one third octave band analysis was useful. For it, the digital

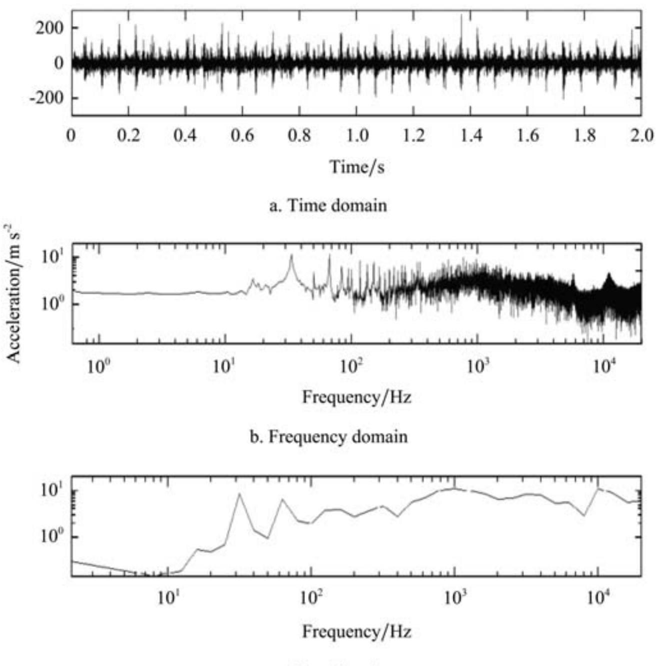

Figure 3 A sample of signal transforms

one third octave filter was suggested in ISO 5349, designed in DELPHI software and narrow band signals were changed to broadband (one third octave) signals by this filter. A sample of signal transforms from time domain to frequency domain and from frequency domain narrow band to frequency domain broadband was shown in Figure 3.

4 Results and discussion

This paper presents the results of analyzing the time and frequency domain signal spectrum in stationery condition in 5 levels of engine speed and 6 levels of diesel- biodiesel fuel blends. The experimental design for vibration measurement was considered as a 6 levels of fuel blends and 5 levels of engine speeds with balanced factorial experiment based on a completely randomized design. The vibration acceleration rms values were also statistically analyzed. Identification of differences in response of vibrations to the fuel blends and engine speeds and axes are based on the outcome of these tests. Extra analysis was carried out to determine the interaction between the fuel blends and engine speeds and axes for each treatment separately.

4.1 Time domain vibration acceleration

In contrast, the vibration time domain signal for diesel fuel at 2,000 r m^{-1} engine speed is shown in Figure 4 in three axes of lateral, longitudinal and vertical. The acceleration amplitude for vertical, longitudinal, and lateral axes is among the ±120, ±100, and ±80 m s^{-2}, respectively. Mainly, these values in longitudinal axis are more than lateral axis.

Figure 5 shows the vibration time domain signal of vertical axis at 2,000 r min^{-1} engine speed for different fuel blends. The vibration amplitudes are most for B10 and B15 and the least for B100 and B20. The reason of vibration acceleration decline with an increase in the biodiesel ratio in diesel-biodiesel fuel blends, can be due to the more complete combustion in pure biodiesel.

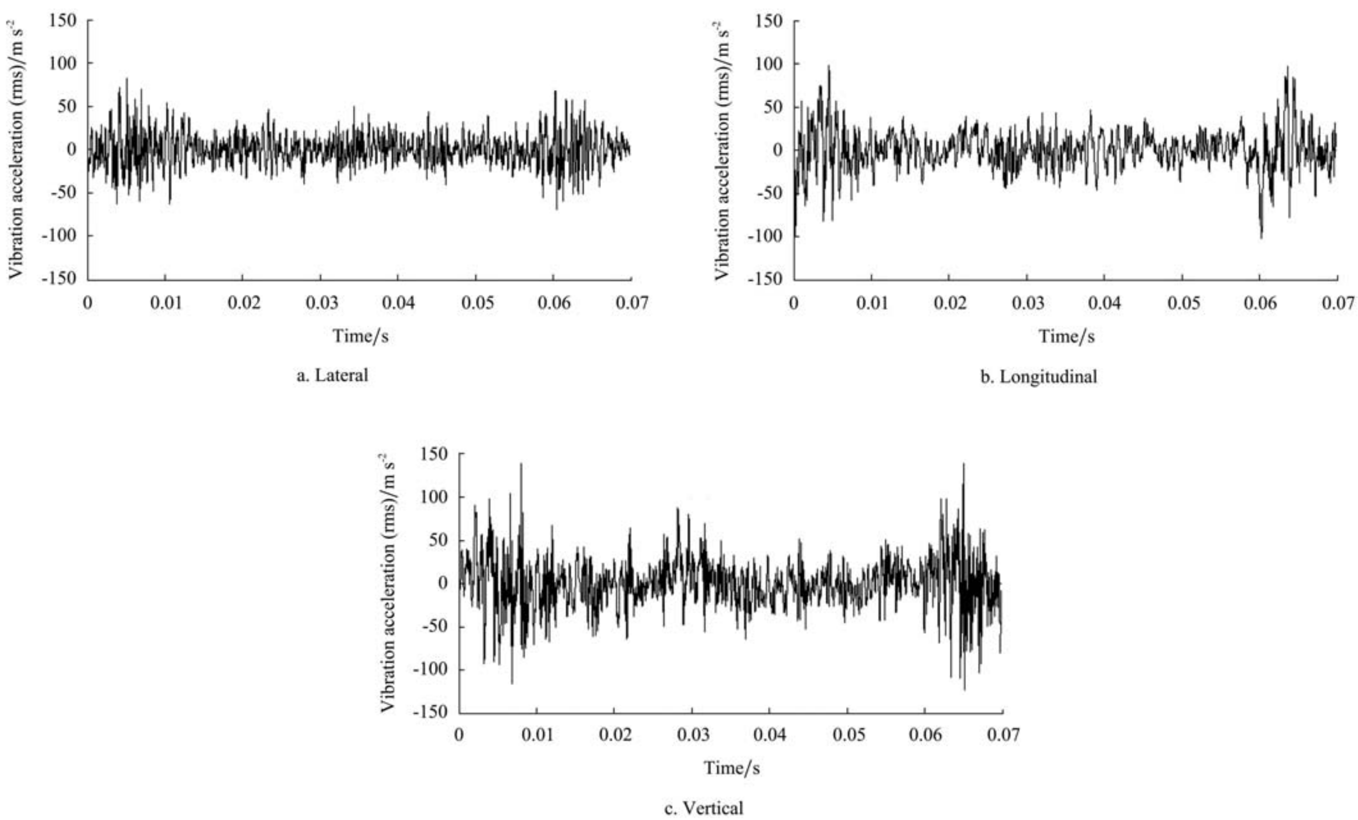

Figure 4 Time domain vibration spectrum-engine position-diesel fuel-2000 r min^{-1}

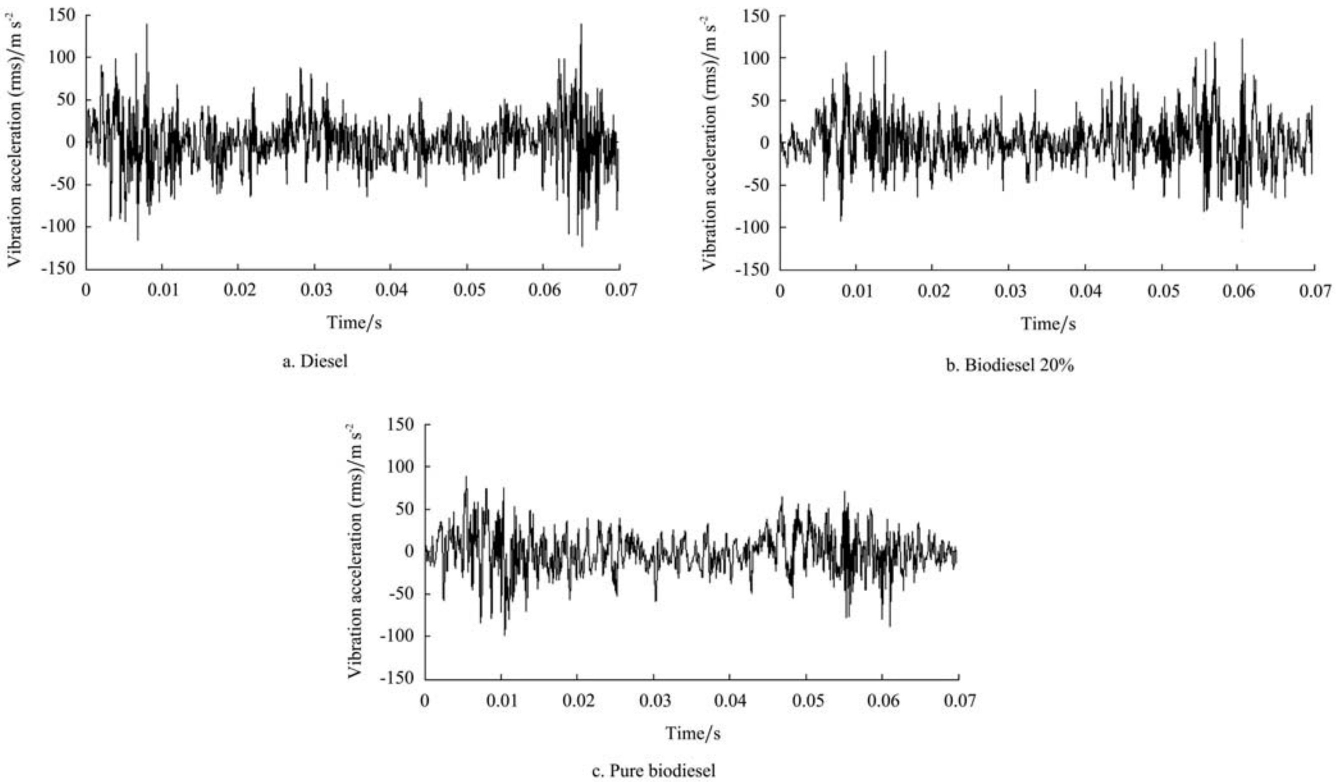

Figure 5 Time domain vibration spectrum-engine position-2000 rmin^{-1}-vertical axis

4.2 Statistical analysis of vibration acceleration in time domain

The rms acceleration values for the total engine speed and fuel blends for vertical (z), lateral (y) and longitudinal (x) orthogonal axes were obtained using Equation (1). Statistical analysis in SAS software was used to evaluate the significant difference between the two-way interaction. Duncan’s Multiple Range test was used to compare the mean values of the treatments. Mean values were considered significantly different in 1% level.

The results indicated there were important differences in the magnitude of rms (Table 3). The rms of vibration acceleration was significantly affected by engine speed, fuel blends and the axes.

Table 3 Position and engine speeds interactions

Source of variation	DF	Vibration acceleration (rms)
Rep	2	185.64*
Engine speed/s	4	126.68*
Fuel blends/f	5	64.38*
Axis/a	2	1121.05*
S*f	20	7.75*
S*a	8	4.93*
F*a	10	8.41*
S*f*a	40	1.58^{ns}

Note: *means prominent in 1% level and ns means non prominent.

A mean value comparison of engine speeds and fuel blends interactions is shown in Figure 6. As it is observed from Table 3, the trend of increasing the vibration from 1,400 to 2,200 r min^{-1} is consistent and linear for all fuel blends. The vibration rapidly increases from 1,800 to 2,000 r min^{-1} for all fuel blends. The least vibration acceleration rms value belongs to 1,400 r min^{-1} and the most vibration acceleration rms belongs to 2,200 r min^{-1}. The results of this research confirmed the findings of Raff (Raff and Perry, 1973). He proved that the increase in forward speed in the position of the engine increases the noise and vibration acceleration in a petrol engine. Also Taghizadeh showed that vibration total value rises with the increase of the engine speed. According to his results, most of risings are at 1,800 and 2,000 r min^{-1} (Taghizadeh et al., 2007). The other researchers showed the similar results for diesel engines (Dewangan and Tewari, 2008; Dewangan and Tewari, 2009; Salokheh et al., 1995; Tiwari and Gite, 2002; Tewari et al., 2004; Mehta et al., 1997).

Comparison of the mean values of fuel blends and axes interactions is shown in Figure 7. It is observed that the magnitude of vibration acceleration in vertical axis is much more than longitudinal and lateral axes, and in longitudinal axis it is more than that in lateral axis. The reason for the high amount of acceleration in vertical axis is the vector of engine strokes. The results of this research are confirmed by the findings of Salokheh et al. (1995), Tiwari and Gite, (2002), Tewari et al.(2004), and Mehta et al.(1997).

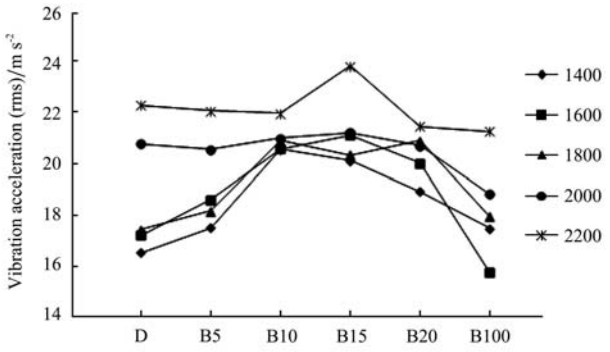

Figure 6 Engine speeds and fuel blends interactions

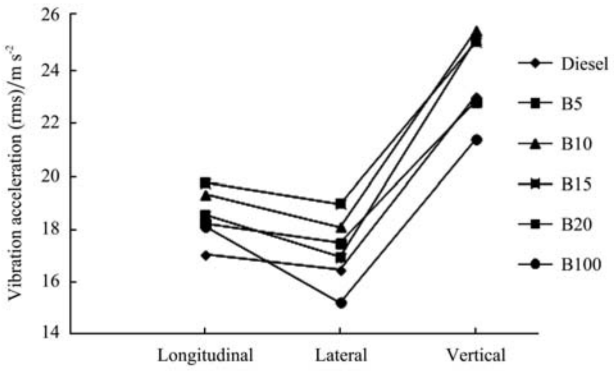

Figure 7 Fuel blends and axes interactions

The most important discussion in this study is the effect of the fuel blends on the engine vibration. The vibration rms values for various types of fuel blends at different engine speed are in the range of 15.76 to 23.82 m s^{-2} (Figure 6, Figure 7 and Figure 8). The vibration rms values do not vary significantly for fuel blends of B10, B15 and B20 with increase of the engine speed from 1,400 to 2,200 r min^{-1}. However, for fuel blends of D100, B5 and B100, the rms values increase with rising of the engine speed from 1,800 to 2,200 r min^{-1}. In all engine speeds, the minimum rms values were observed for B100, D100, B5 and B20 fuels and the maximum values were observed for B15 and B10 fuel blends. The results also showed in the lateral and longitudinal directions, the vibration minimum rms values was related to B100, D, B5 and B20 fuels, and the maximum rms was related to B10 and B15 fuel blends. In vertical direction the vibration maximum rms was also related to B10 and B15 fuel blends. However, it was observed that in all fuel blend, the acceleration was minimal in the B100, B5 and B20 fuels. The results of this research were confirmed by the findings of Taghizadeh who proved the lowest vibrations were in B20 for the two modes. In the first case, the highest amount of vibration was created by fuels B10, B15, B30 and B50 (Taghizadeh et al., 2012).

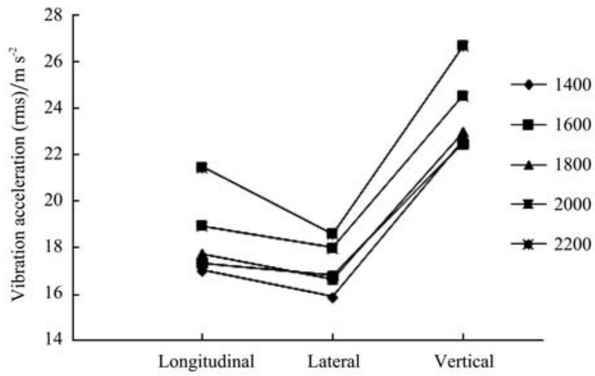

Figure 8 Engine speed and axes interactions

There are so many reasons that could be considered as a cause of the vibration variations such as cetane number, flash point, viscosity, lubrication properties, thermal properties, physical properties, chemical and molecular structure of all fuel blends. Also engine power, torque, specific fuel consumption (sfc) and exhaust emissions (NOx, CO, HC) should be considered for choosing the most suitable fuel blends (Rahimi et al., 2009).

Biodiesel fuel contains 10% oxygen by weight. Adding oxygenated compounds to the new blend seems to slightly reduce the engine power and torque and increase the average sfc for various speeds. The possible medium that can influence vibration is the level of oxygen in fuel blends. Another possible factor might be related to the injection and spraying characteristics of fuel (Taghizadeh et al., 2012).

Using of biodiesel reduces engine power due to the lower heating value of biodiesel. Also, it has reported that there is no significant difference in engine power between pure biodiesel (B100) and diesel fuel (Aydin and Bayindir, 2010; Xuea et al., 2011). This is inconsistent with the results that the vibration of pure biodiesel fuel is higher than that of diesel fuel. Also, pure biodiesel fuel viscosity is more than diesel fuel (Aydin and Bayindir, 2010; Xuea et al., 2011). Therefore, injection and powder in the injector nozzle may not perform properly. Another factor that can be related the cetane number for fuel blends needs to be further investigated. This has proposed that by increasing the biodiesel volume percentage in biodiesel-diesel fuel blends, the cetane number will be increased (Aydin and Bayindir, 2010). Another important factor, the injection advance should be reset with changing of the fuel blend. The injector pump for testing engine was not able to operate as well. Generally, injection advance, cetane number, and viscosity could be important factors which affect vibration values (Taghizadeh et al., 2012).

Ghobadian reported that the mean value of engine SFC of B10, B20, B30, B40, and B50 fuel blends for various engine speeds are 4.0%, 0.8%, 0.6%, −2.2% and 1.4% higher than net diesel fuel respectively (Ghobadian et al., 2009). Hence, these factors at B5 and B20 fuel blends have the appropriate conditions that cause a better combustion and less knocking in the engine under test. So, the ideal percentage of biodiesel and diesel blends, in order to reduce the vibration and improve other properties of fuel and its performance in the engine is B20 and B5 respectively. Figure 8 is also justified the same results of engine speed and axes trends with Figure 6 and Figure 7.

4.3 Frequency domain vibration acceleration

Figure 9 shows the vibration acceleration (rms), as a function of frequency, in 1/3rd octave bands between 2.15 and 20,000 Hz for the Xh (longitudinal), Yh (lateral) and Zh (vertical) axes and compares the different axes for power tiller engine. The results showed the vibration acceleration peaks was observed between 10 and 100 Hz and around 1,000 Hz. The first peak of vibration occurred in engine combustion frequencies 20, 23.33, 26.66, 30, 33.33, 33.33 and 36.66 Hz in 1,200, 1,400, 1,600, 1,800, 2,000 and 2,200 r min^{-1} respectively. It was observed that with the increase in forward speed in three axes, the vibration acceleration increased almost at all of the frequencies. However, the vibration acceleration increase trend was more in high speed of the engine. Also it was observed that the amount of vibration acceleration magnitude in vertical axis was much more than that in the other two axes, and also in longitudinal axis was more than in lateral axis. The reason for the high acceleration values in vertical axis was the vector of engine piston strokes. Dewangan showed that the axes have a prominent effect on measured vibration (Aydin and Bayindir, 2010; Xuea et al., 2011). Also the other researchers showed the same results for the other diesel engines (Taghizadeh et al., 2012; Sam and Kathrivel, 2006; Sam and Kathrivel, 2009; Taghizadeh et al., 2007).

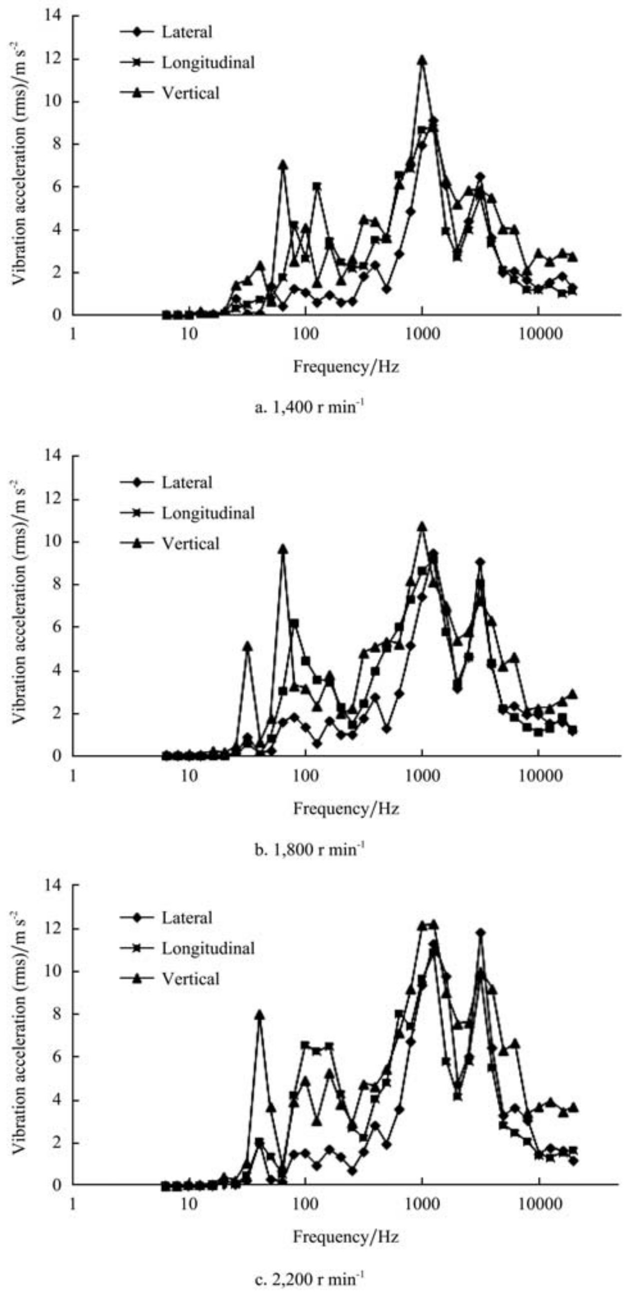

Figure 9 Relationship between vibration acceleration (rms) in three axes and frequency spectrum at 1/3 octave band in three engine speed

Figure 10 showed the vibration acceleration (rms), as a function of frequency, in 1/3rd octave bands between 2.15 nd 20,000 Hz for different fuel blends. The results showed that different fuel blends have almost same trends and B100 has less vibration acceleration value, particularly in frequency less than 1,000 Hz. But between 1,00 and 20,000 Hz diesel-biodiesel has the same trends and the least vibration. It totally could be claimed the changing the fuel blends has a negligible effect on the vibration performance of the power tiller engine. Also the vibration acceleration produced by B100 is the least between all kinds of fuel blends. The reason for reducing the vibration acceleration with biodiesel in power tiller engine may be the more complete combustion that happens in the engine under test.

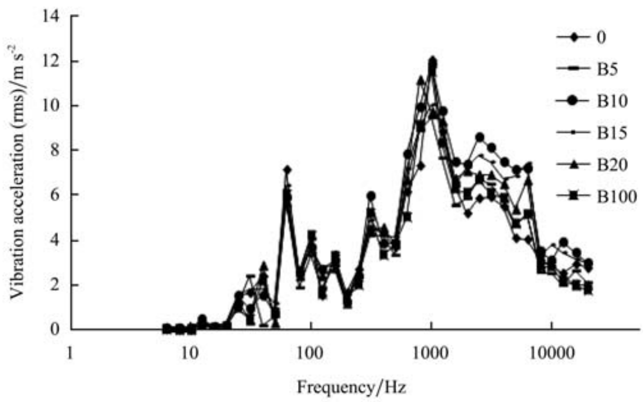

Figure 10 Relationship between vibration acceleration (rms) and frequency spectrum at 1/3 octave band in 1,400 r min^{-1} engine speed in different fuel blends

5 Conclusions

This study carried out for investigating the vibration of different diesel-biodiesel fuel blends in power tiller engine. The main goal was to present fuels with the minimum vibrations. For this reason the time domain signals were analyzed in five levels of engine speed (1,400, 1,600, 1,800, 2,000 and 2,200 r min^{-1}), three axes (vertical (z), lateral (y) and longitudinal (x)) and six fuel blends (D100, B5, B10, B15, B20 and B100) for a diesel engine. Results were considered by Signal processing and statistical analysis. The results showed that at all engine speeds, the dominant frequency was the piston stroke frequency of the engine and the frequency of vibration increased by raising the engine speed. The experiments indicated that the magnitude of vibration of the power tiller engine depends on the axis of measurement, engine speed and the fuel blends. Vibration acceleration was significantly affected by engine speeds and the increase in forward speed due to the increase in vibration acceleration rms. Results of experiments revealed that the vibration acceleration was significantly affected by the axis of measurement. The vibration acceleration value in vertical axis was more than that in the other two axes and in the longitudinal axis was more than that in lateral axis. Fuel blends significantly influenced the vibration. It demonstrated that B100, B5 and B20 have the lowest vibration, and B15 and B10 have the highest vibrations.

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